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THE POLYPHASE RESONANT CONVERTER MODULATOR FOR PULSE POWER AND PLASMA APPLICATIONS*

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Abstract

This paper describes a new technique to generate high voltage pulses (100 kV and up) with high peak power (10 MW and up) and high average power (1 MW and up) from a low voltage input source (e.g. +/- 1.2 kV). This technology is presently being used to provide cathode pulse modulation for the Spallation Neutron Source (SNS) accelerator klystron RF amplifiers, which operate to 140 kV 11 MW peak power and 1.1 MW average power. The design of the modulator, referred to as the Polyphase Resonant Converter-Modulator takes advantage of high-power component advances, in response to the needs of the traction motor industry (in particular, railroad locomotives), such as Insulated Gate Bipolar Transistors (IGBT's) and self-clearing metallized hazy polypropylene capacitors. In addition, the use of amorphous nanocrystalline transformer core alloy permits high frequency voltage and current transformation with low loss and small size. Other unique concepts embodied in the converter-modulator topology are polyphase resonant voltage multiplication and resonant rectification. These techniques further reduce size and improve electrical efficiency. Because of the resonant conversion techniques, electronic "crowbars" and other load protective networks are not required. A shorted load detunes the circuit resonance and little power transfer can occur. This yields a high-power, high-voltage system that is inherently self-protective. To provide regulated output voltages, Pulse Width Modulation (PWM) of the individual IGBT pulses is used. A Digital Signal Processor (DSP) is used to control the IGBT's, with adaptive feedforward and feedback control algorithms that improve pulse fidelity. The converter-modulator has many attributes that make it attractive to various pulse power and plasma applications such as high power RF sources, neutral beam modulators, and various plasma applications. This paper will review the design as used for the SNS accelerator and speculate on related plasma applications.

I. INTRODUCTION

The SNS accelerator is a new 1.4 MW average power beam, 1 GeV accelerator being built at Oak Ridge National Laboratory (ORNL). The accelerator requires 15 converter-modulator stations each typically providing 10 MW pulses with up to 1100 kW average power. Two variants of the converter-modulator are used, 80 kV and 140 kV, which share a common topology with many interchangeable parts. Each converter modulator derives its bus voltage from a standard 13.8 kV to 2100 Y (1.5 MVA) substation cast-core transformer. The substation also contains harmonic traps to satisfy IEEE 519 and 141 regulations. Each substation provides input to a 6-pulse Silicon Controlled Rectifier (SCR) subsystem, that produce the regulated positive and negative DC rails for the high-frequency IGBT inverters, compensating for system voltage changes from no load to full load, and providing a soft-start function. Energy storage is provided by specially-developed low-inductance self-clearing metallized hazy-polypropylene capacitors. Internal dielectric short-circuit failures are automatically cleared by fusing action, resulting in lifetime of exceeding 300,000 hours. As in traction-motor drive application, these capacitors are hard-bussed in parallel. Three "H-Bridge" IGBT switching networks are used to generate the polyphase 20 kHz primary drive for the step-up transformers.. The 20 kHz drive waveforms are time-gated to generate the desired klystron pulse width. PWM of the individual 20 kHz pulses produces regulated output waveforms with DSP based adaptive feed-forward and feedback techniques. The step-up "boost" transformer design uses cut "C- cores of amorphous nanocrystalline material providing low core-loss at the design flux levels and switching frequencies. Shunt capacitance is used on the transformer secondary to boost output voltage by resonating with the transformer leakage inductance. The resonant voltage multiplication, and the three-phase wye-connected secondary windings result in considerable line-line input to the high-voltage six-pulse output rectifiers. The transformers are wound with a 1:19 turns ratio, but the line-line output voltage ratio is over 1:60. With the appropriate transformer leakage inductance and peaking

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capacitance, zero-voltage-switching of the IGBT's is also achieved, minimizing IGBT switching losses. The resonant topology has the added benefit of being deQed in a klystron fault (shorted output) condition, with little energy transfer during an arc-down situation. This design feature obviates electronic crowbars and similar protective networks.

II. HARDWARE DESIGN

The system block diagram of the SNS converter-modulator is shown in Figure 1. The fabrication of the converter-modulator systems is by means of industrial fabrication contracts for the four major subsystems, consisting of: A) the utility substation, B) the SCR subsystem, C) the converter-modulator subsystem, and D) the equipment control rack. The converter-modulator assembly is a "build-to-print" contract, the others, "build-to-specification", all awarded to the lowest-cost qualifying bidder. This acquisition methodology has provided the lowest cost with the best qualified individuals to the SNS project.

A. *60 Hz Systems*

The individual converter-modulator substations contain harmonic-frequency traps (5^{th} and 7^{th}) to comply with IEEE 519 and 141 standards. To maximize substation efficiency (~99%) standard "traction-drive"-style vacuum cast core transformers and filter coils are used. Since the unit contains no oil, oil-containment, fire suppression equipment, and environmental impact statements are not required. The topology further simplifies installation: a single utility cable pull for the input and output with a lightweight, two-piece, design that can be "forked" into position onto the outdoor pad. To maintain balanced line currents and core flux, the neutral is not grounded. With the repetitive pulsed loading of the transformer, there are no engineering (e.g. harmonic mitigation) or cost advantages to a 12-pulse SCR subsystem. A 6-pulse system is less expensive and easier to filter. The substations for the SNS Accelerator are manufactured by *Dynapower Corporation,* located in Burlington, Vermont.

B. *SCR Subsystem*

Each substation is followed by an SCR subsystem, located indoors, in the klystron gallery. A single utility pull using armored triplex between the substation and SCR regulator simplifies the interconnection between the pad and the indoor equipment. The SCR subsystem produces nominal DC outputs 0f +/- 1200 V, at 400 A. and accommodates incoming line voltage variations resulting from network, transformer, and trap impedances, from no-load to full load, and provides the soft-start function. This unit is 99.5% efficient and is manufactured by *Dynapower Corporation.*

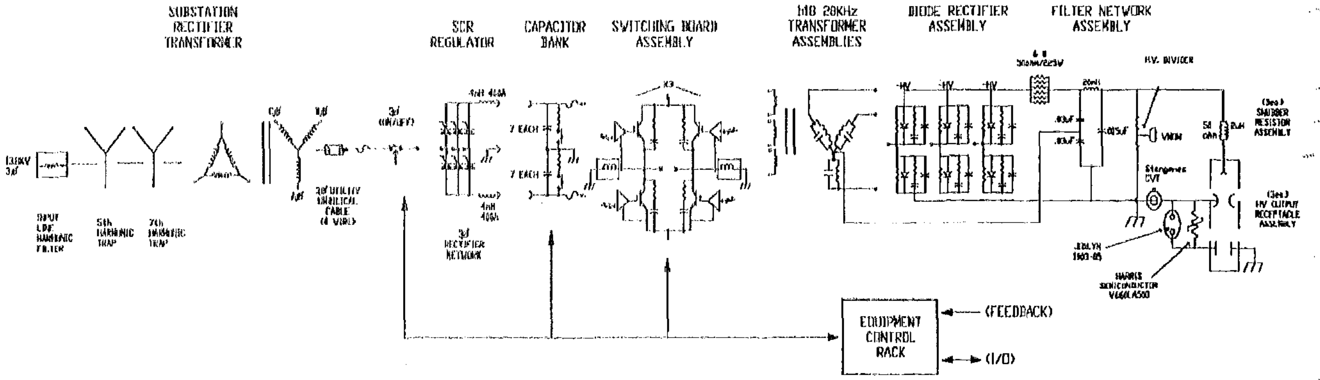

Figure 1. System Block Diagram

C. *Converter Modulator Assembly*

A view of the completed converter modulator assembly is shown in Figure 2. The oil tank, safety enclosure, and water distribution panel are the prominent features that can be noted in this figure. *Dynapower Corporation* won the contract for the build-to-print converter modulator assembly. The first production converter modulator assembly will be delivered to ORNL in the 4^{th} quarter of fiscal year 2002.

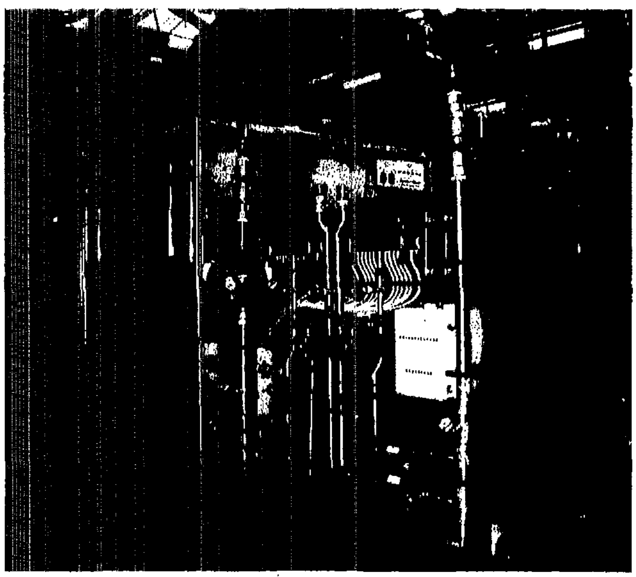

Figure 2. Converter Modulator Assembly

1) Self-Healing Capacitors

The energy storage capacitors are similar to those used in traction-drive applications. *Thomson Passive Components* (AVX), located in Saint-Appollinaire, France worked with LANL to develop a lower-inductance capacitor for the 20-kHz, switching application. Internal fabrication techniques have been optimized to provide more equal current distribution within the capacitor and to minimize internal series inductance. The all-film design yields excellent energy density and the use of high-ohm metal-electrode deposition ensures current-balance through all the internal foil-packs. As in traction-drive applications, the capacitors use metallized hazy-polypropylene dielectrics that fuse or "clear" any internal fault, and therefore do not fail in the short-circuit mode. Also, at this voltage rating (1.5 kV), there has not been a recorded internal capacitor bus failure. With converter-modulator operation at full output and maximum bank voltage of 1.25 kV, the capacitor lifetime is calculated to be over 300,000 hours. A view of the capacitor racks is shown in Figure 3.

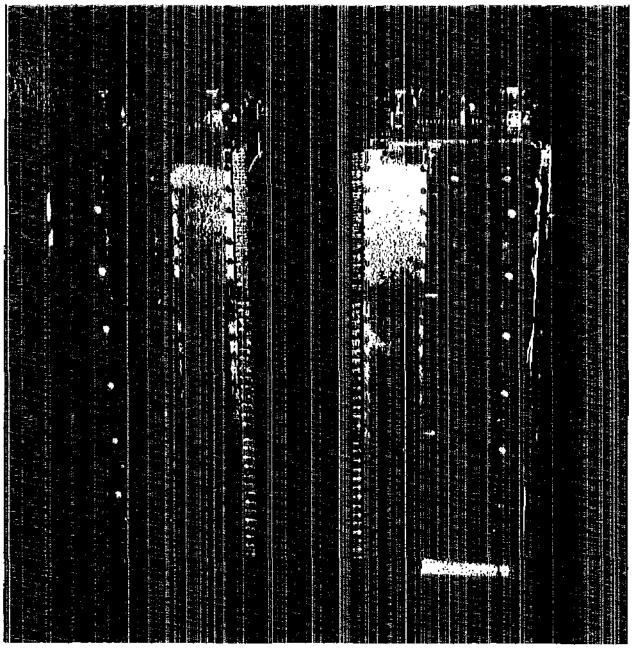

Figure 3. Capacitor Racks

2) IGBT Switch Plate Assembly

The IGBT switch plate assemblies are designed to be easily removable, like a large printed circuit card, so that maintenance and repair can be accommodated off-line. Sliding high-current contacts of multilam louvers provide an interface to the transformer primary bus-work, that terminate on the modulator tank lid. Each switch plate contains four IGBT's in an "H-bridge" configuration. The IGBT device is in the 3300-Volt, 1200-Ampere family of devices. The *Mitsubishi* (Powerex) CM-1200HB-66H has been used successfully for the majority of operations. The mechanical design of the switch plate assembly puts the IGBT terminals directly opposite one-another (face-to-face), to provide low-inductance interconnection. This results in a rail-to-rail inductance (V+ to V-) of ~4 nH. Low inductance (~9 nH), high frequency IGBT bypass capacitors have been developed by *General Atomics Energy Products* (formerly Maxwell) and are shown in Figure 4. The resulting low inductance of the IGBT switch plate network of ~7 nH that is essential to minimize overshoot and ringing from the multi-kA 20 kHz switching, having dI/dT's of ~10 kA/uS. The IGBT switch-plate assemblies must switch the peak power of the system, 11 MW, not just the average power. With the high peak powers involved, additional "on-board" energy storage is provided by 8 each 10 uF, 2 kV capacitors, also manufactured by *General Atomics Energy Products.*

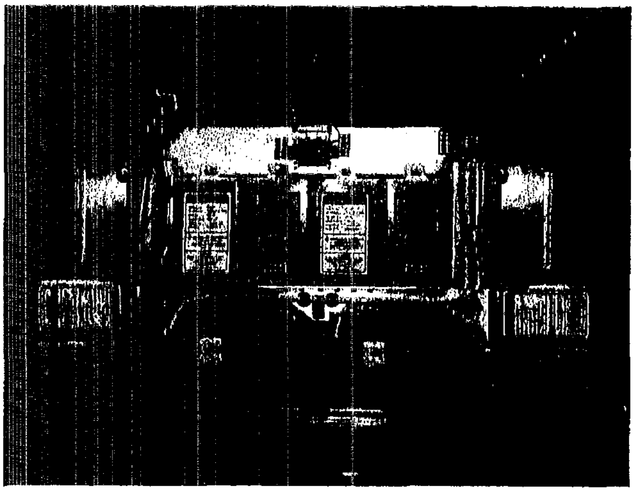

Figure 4. IGBT Switch Plate Assembly

3) Amorphous Nanocrystalline Boost Transformers

The development of the amorphous nanocrystalline transformer core material was another long-lead development for this project. This was successfully completed by *National-Arnold Magnetics* in Adelanto, CA. The characteristics of the nano material are given in the following table:

Mu	50,000
Lamination Thickness	.0008"
Lamination Insulation	1 µM Namlite
Stacking Factor	~90%
Bsat	12.3 kG
Core Loss (our use)	~300 W
Core Weight (our use)	~95 lbs
Power (each core)	330 kW

Table 1. Nano Material Characteristics

The amorphous nanocrystalline material has exceptional performance and the added benefit of 'zero-magnetostriction". It does not vibrate or make significant noise with excitation. Additional benefits to the nanocrystalline material are realized by the specific lamination insulation process. The *National-Arnold* "Namlite" process is applied after the core has been wound and the core has been re-crystallized into the nano state. The resulting 1 micron insulating coating (an oxidation process) is shown in Figure 5.

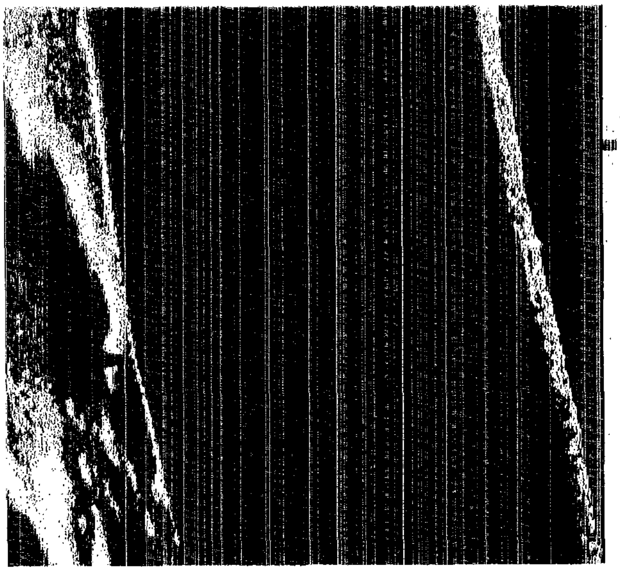

Figure 5. 1µM Namlite Coating

The Namlite coating results in a high stacking factor, higher magnetizing inductance, lower core loss, lower core flux, and improved system efficiency as compared to previous technologies. The windings are two single-layer solenoids with a turns ratio of 1:19, for the 140 kV output configuration. Although the transformers are wound with a ratio of 1:19, the line-line output is about 1:60. Unlike previous power transformers having the same "volts-per-turn" for both the primary and secondary, this design generates multiple volts-per-turn on the secondary. The core flux expended, however, is that of the primary. It is important to note that the specific turns ratio is not chosen on a basis of the required output voltage, but on the effective leakage inductance produced by the number of turns and related winding space. A broad range of winding turns is possible as long as peaking capacitance is re-tuned for the desired output and IGBT switching conditions. The combination of leakage inductance and resonating capacitance strongly affect the required switching characteristics of the IGBT's. An optimized resonance of leakage inductance and peaking capacitance result in "zero-voltage-switching" for the IGBT's. The zero-voltage-switching characteristic minimizes the IGBT switching power loss, and turn-on is "soft", without forced-commutation (and losses) of the opposite IGBT free-wheeling diode. The resonating capacitors are developed by *General Atomics Energy Products* and circulate many MVAR at 20 kHz, with 100% voltage-reversal to ~160 kV p-p. A view of the completed nano-crystalline-core boost transformer assembly is shown if Figure 6. The overall transformer height is about 24" with a total weight of ~150 lbs.

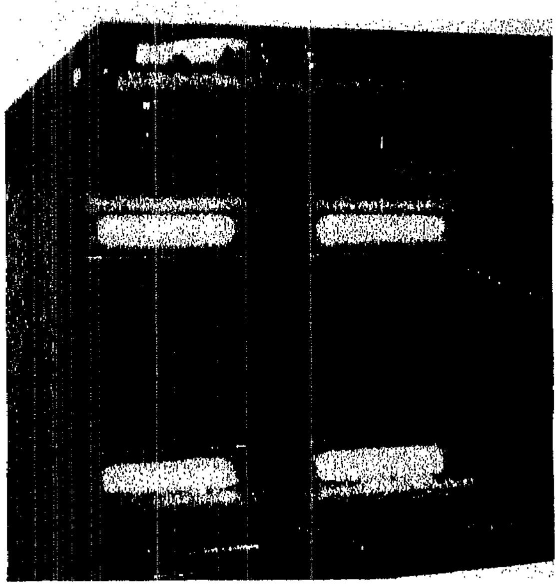

Figure 6. 330 kW Nanocrystalline Boost Transformer

4) Resonant Rectification System

To provide six pulse rectification of the 20 kHz, ~140 kV line-line voltages, resonant-rectification techniques are used. Capacitors are placed in parallel with groups of rectifier diodes. Low-loss, fast-recovery diodes are still necessary. Ion-implanted diodes with 1,600-volt PRV, 70-Amp ratings, manufactured by *IXYS* are used in the 140 kV modulator assemblies. The circuit effect of the added rectification capacitance is similar to that of the transformer shunt peaking capacitors, and must be considered in the analysis of the transformer tuning. The resonant-rectification capacitors isolate switching transients and "Miller" (to ground) capacitance from the diodes. The Miller capacitance can cause significant over-voltage of diodes near the high-voltage end of the stack. The resonant rectification capacitors effectively swamp this condition. The capacitors are manufactured by *General Atomics Energy Products* and must have good tolerances, small size, and low equivalent series resistance and dissipation factor.

5) Output Filtering

Output filtering is provided by a standard "Pi-R" network. The input resistance helps mitigate ringing of the rectifier circuits. The lowest theoretical output ripple frequency from the 6-pulse, 20-kHz rectifier is 120 kHz. Due to phase-phase and bipolar rectification imbalances, 20 kHz and 40 kHz components are possible and have been observed. Filter capacitance values are chosen to provide adequate filtering yet minimize stored energy. The stored energy is wasted at the end of each klystron pulse. With 120 kHz ripple frequency, high efficiency with good filtering can be attained.

D. Equipment Control Rack

The operator and control room interface for the converter-modulator is via the equipment control rack.

This rack controls and monitors all the power conditioning functions, such as the SCR subassembly, capacitor banks, IGBT switching network, oil tank assembly, and output load parameters. The rack includes functions for (Ethernet) "EPICS" based control I/O, Allen-Bradley PLC with local I/O and station keeping, fast electronic monitors, and controls. This includes personnel-protection interlocks as well as all electronic fault-protection systems. The fault-protection systems have the appropriate thru-put delays and latching function to minimize the probability of equipment damage. The Digital Signal Processor (DSP)-based control system has adaptive feed-forward and feedback networks with learning algorithms to generate voltage-regulated modulator output pulses, using Pulse-Width Modulation (PWM) of the individual IGBT pulses, to compensate for capacitor bank droop and network overshoot. Figure 7 shows the modulator output at 80 kV without adaptive controls and Figure 8 shows the 80 kV output with adaptive controls. The complete equipment control rack is manufactured by *Z-TEC Inc.* located in Albuquerque, NM.

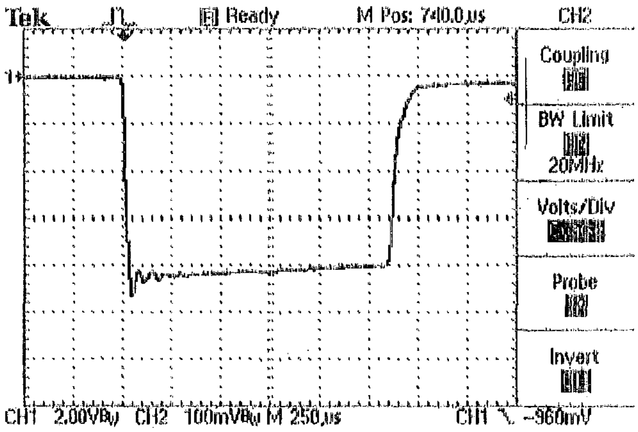

Figure 7. 80kV Output Pulse, 20kV/Division

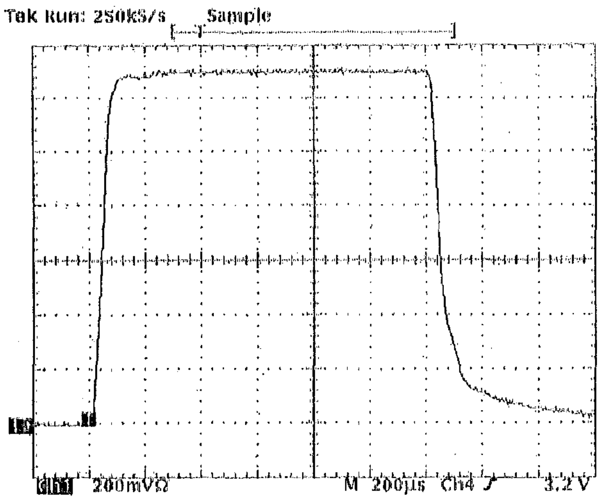

Figure 8. 80kV Output with Adaptive Feedforward/Feedback

III. OPERATIONAL RESULTS

The fabrication of the converter-modulator started in December 1999. With slightly over a year of construction, the modulator made its first full-power and voltage pulse January 17, 2001. Figure 9 shows the transformer primary switching waveforms before resonant conversion and rectification of the output. Figure 10 shows the resulting output with 140 kV at the end of the pulse.

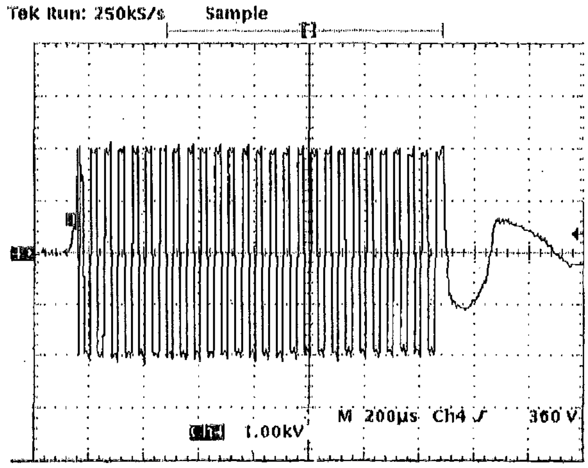

Figure 9. Transformer Primary Waveform

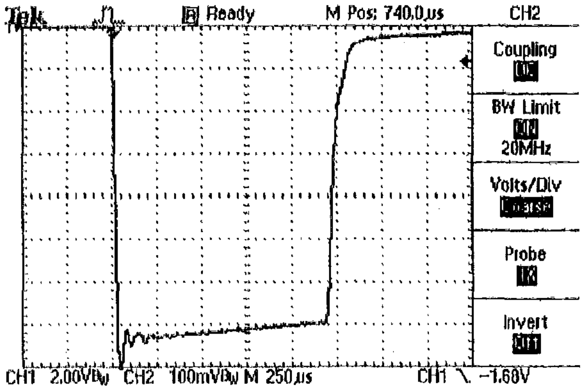

Figure 10. 140kV Output Pulse, 20kv/Division

Since that time, we have operated various klystrons and equipments in support of the SNS project and partner laboratories. Numerous upgrades to the infrastructure (e.g. electrical utilities and cooling water) have also been required to facilitate operations to achieve our required average power.

We have operated the system to the limit of our loads, 130 kV at ~500 kW average power. This operational level completely tests the Marconi 2.5 MW, 402 MHz klystron and the CPI 2.5 MW, 805 MHz klystron. Testing to the full 140 kV output with ~ 1MW input power will commence once the large 5 MW, 805 MHz klystrons are received from Thales. These tubes are scheduled for an August 2002 delivery. No doubt, as we provided utility service to the various SNS operations, corrections and changes have been made to the design to improve reliability. The two most significant changes relate to the IGBT gate drive voltage and the HV secondary winding of the boost transformer. Higher IGBT gate drive than the standard +/- 15 volts is required for high power 20 kHz resonant switching. The change to the boost transformer winding is that the high-voltage secondary windings will now be vacuum cast by the converter-modulator vendor, *Dynapower Corporation.*

A. Crowbar Tests

Extensive fault testing has also been performed with three times the anticipated SNS high-voltage cable length. These tests have been performed at voltages higher (~145 kV) than anticipated for our operation. Figure 11 shows a 130 kV crowbar test into a 5 joule wire.

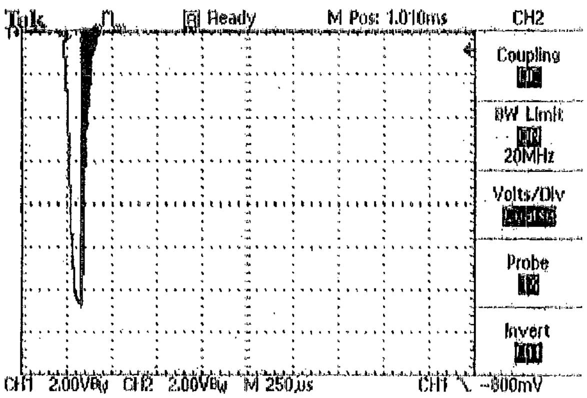

Figure 11. 130kV Self-Break Crowbar Test

This test shows the result when the IGBT switching is disabled. Protection of the klystron is not dependant on the inhibition of IGBT switching and IGBT reliability is not dependant on interruption of gate drive during a klystron arc-down. Figure 12 shows an arc-down event with the IGBT's continuing to switch, which did not fuse the test wire. In the shorted condition, the resonance of the converter-modulator is deQed, and little power transfer results. The low primary drive voltage coupled into the relatively high leakage inductance of the transformer does not even create an over-current situation for the IGBT's. These results match our modeling.

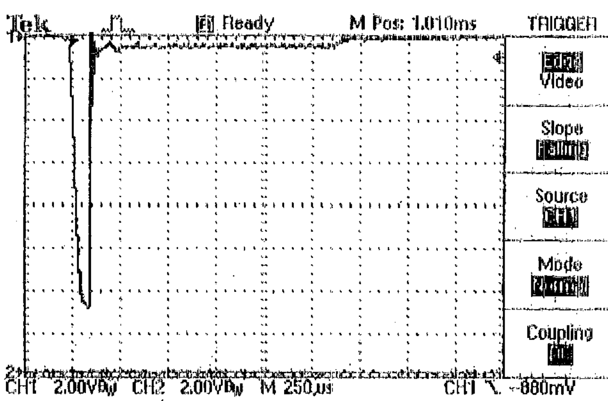

Figure 12. 130kV Run-On Fault Test

IV. PLASMA APPLICATIONS

The overall system topology is very attractive for plasma applications. The high power capability coupled with the self-protective feature and a regulated output enable the use of this technology for various plasma loads. Plasmas frequently arc-down and regulated voltages are desired for process control. Fusion applications could immediately benefit for such uses as neutral beam modulators, Electron Cyclotron Heating (ECH) systems, and other tube related RF heating schemes. For Plasma Source Ion Implantation (PSII), switching frequencies may be able to be scaled appropriately for short pulse (20 to 50 uS) application. The need for "blanking" electronics could be avoided and a decrease in physical size would result as compared to other standard approaches now in use. Lower power polyphase resonant converters are certainly viable for beam-line implanters and other HV related processes requiring high precision. The resonant techniques may find use in high frequency barrier discharge plasma's for flue gas remediation systems.

V. CONCLUSION

The polyphase resonant converter-modulator has demonstrated several new design methodologies that are expected to revolutionize long-pulse and "CW" modulator designs. These new technologies include special low inductance self-clearing capacitors, large amorphous nanocrystalline cut-core transformers, high-voltage and high-power polyphase resonant conversion, and adaptive power supply control techniques. Design economies are achieved by the use of industrial traction-drive components such as cast power transformers, IGBT's, and self-clearing capacitors. The compact and modular design minimizes on-site construction and a simplified utility interconnection scheme further reduces installation costs. The design does not require HV capacitor rooms and related crowbars. By generating high-voltage when needed, reliability and personnel safety is greatly enhanced. .

VI. ACKNOWLEDGEMENTS

The success of the polyphase resonant converter-modulator would not have been possible without the efforts of the talented design crew and fabrication technicians. These individuals include David Miera, Jacqueline Gonzales, Marvin Roybal, John Sullard, Diego Jaramillo, Sean Apgar, and Pete Trujillo.